2011

Effects of salinity and sand content on liquid limit and hydraulic conductivity

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Abstract

Soil conditions of construction sites have become worse than ever due to the overpopulation in the metropolitan areas throughout the world. Likewise, the prevention of environmental risks due to individual activities is one of the most important subjects in the geo-environmental problems. Saline soils may induce several problems in geotechnical engineering projects such as infrastructure embankments, road construction and clay liners. Effect of the various concentrations of sodium chloride (NaCl) on several different soils including bentonite, kaolinite and fine sand mixtures has been evaluated. In addition, influence of salinity and the period of submergence on the hydraulic conductivity of soil samples collected from a certain area of east coast of India was investigated. The results show that the liquid limit of the mixtures generally decreases with an increase in the salt concentration. Liquid limit decreased significantly with an increase in NaCl concentration up to a certain level. However, a further increase in the concentration does not induce any significant decrease in liquid limit. Furthermore, the soil hydraulic conductivity increase with the salt concentration and with increase in the period of submergence, the hydraulic conductivity of the soil increases asymptotically.

EFFECTS OF SALINITY AND SAND CONTENT ON LIQUID LIMIT AND HYDRAULIC CONDUCTIVITY

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ABSTRACT

Soil conditions of construction sites have become worse than ever due to the overpopulation in the metropolitan areas throughout the world. Likewise, the prevention of environmental risks due to individual activities is one of the most important subjects in the geo-environmental problems. Saline soils may induce several problems in geotechnical engineering projects such as infrastructure embankments, road construction and clay liners. Effect of the various concentrations of sodium chloride (NaCl) on several different soils including bentonite, kaolinite and fine sand mixtures has been evaluated. In addition, influence of salinity and the period of submergence on the hydraulic conductivity of soil samples collected from a certain area of east coast of India was investigated. The results show that the liquid limit of the mixtures generally decreases with an increase in the salt concentration. Liquid limit decreased significantly with an increase in NaCl concentration up to a certain level. However, a further increase in the concentration does not induce any significant decrease in liquid limit. Furthermore, the soil hydraulic conductivity increase with the salt concentration and with increase in the period of submergence, the hydraulic conductivity of the soil increases asymptotically.

1   INTRODUCTION

Increasing salinity is one of the most significant environmental problems facing Australia. Salinity causes millions of dollars of costly damage to urban infrastructure every year. Saline soils are soils with high levels of salt and it is recognized that the removal of deep-rooted native trees, grasses and vegetation, coupled with flood irrigation techniques have caused the water table to rise, and this has brought excessive amounts of subterranean salt to the surface. The term 'salinity' refers to the total concentration of all soluble salts in the soil. These are typically chlorides, sulphates or carbonates of sodium, calcium and magnesium with the most common salt being sodium chloride (NaCl) used in this study. Climatic trends and human activities such as land clearing and aquaculture activities are also involved in salinisation process. According to the FAO/UNESCO (1990) Soil Map of the World, Australia has 84.7×10^6 ha of salinised area, which is the highest in the world. Additionally, the growing number of port expansion projects in Australia (e.g. Port Botany, Port of Brisbane), application of dredged marine sediments as the backfill material for the counterfort units is becoming more common. However, dredged marine sediments are complex materials due the presence of various salts and chemical pollutants. Many studies have been conducted for determining geotechnical properties of saline soils all over the world. Saline soils have some unfavorable properties such as high compressibility, low bearing capacity and swelling capability (Al-Zoubi, 2008; Moayed *et al.,* 2011). Considering excessive development of urban area and also highways and road networks which are necessary for transportation, civil engineers have to construct significant plans possibly over saline soils. In engineering applications clays will seldom be in contact with demineralised water. Therefore, it is surprising that in the lab characterization of clay mineralization of clay properties still demineralized water is used as a standard.

According to the Unified Soil Classification System (USCS), fine soil grains are finer than 0.075 mm and particles larger than this size are coarse particles. Silt (0.075 mm – 0.002 mm) and clay (fine than 0.002 mm) are fine soils. To classify the fine grained soils (finer than 0.075 mm, silt or clay), plasticity chart (liquid limit vs. plasticity index) is being used. Silt plots below the A-line and clay above the A-line on the plasticity chart, i.e. silts exhibit plastic properties over a lower range of water content than clays having the same liquid limit. However, according to the current standards to measure the liquid limit of soils (e.g. ASTM D4318-10, AS 12889.3.9.1-2002), the liquid limit test is conducted on materials finer than 0.425 mm and not 0.075 mm. It means fine sand particles are included in the liquid limit test, although LL is to be used to classify the fine grained soil particles (finer than 0.075 mm). Authors believe there is inconsistency in the various parts of soil classification methods outlined in standards. The current standards adopt soil particles finer than 0.425 mm to conduct plasticity test as collecting enough soil particles finer than 0.075 mm using sieve analysis is very time consuming. However, this does not justify the inconsistencies in the testing procedures and soil classification methods and the issue should be addressed properly as the soil plasticity may change with the fine sand content.

Because saline soils spread over large parts of Australia our effort in this study is to investigate the effect of salinity level on the various geotechnical parameters namely liquid limit and hydraulic conductivity. The effects of salinity on other soil properties such as compression indices, consolidation coefficient, plastic limit and shrinkage limit will be considered in the follow up papers by the authors. It should be noted that the use of saline water for irrigation followed by surface leaching with rain water is typical in soils under continental monsoonal climates. Therefore, changes in geotechnical and hydraulic properties of soils with different salinity levels are of interest to both geotechnical and agricultural engineers.

2 BACKGROUND

Murray (1999) described that clay minerals are important in a number of geological applications such as stratigraphic correlations, indicators of environments of deposition and temperature for generation of hydrocarbons. In agriculture the clay minerals are a major component of soils and determinant of soil properties. Clay minerals are important in construction where they are a major constituent in brick and tile. The physical and chemical properties of the clay minerals determine their utilization in the process industries. According to Smith (1990), the minerals forming clay are basically the result of the chemical weathering of rock particles and are hydrates of aluminium, iron or magnesium silicate, generally combined in such a manner as to create sheet-like structures only a few molecules thick. Practically all the minerals with a sheeted structure, which are encountered in the very fine soil fraction, belong to a group known as the clay minerals (Terzaghi and Peck, 1993). These sheets are built from two basic units, the tetrahedral unit of silica and the octahedral unit of the hydroxide of aluminium, iron, or magnesium. Most of the minerals of clays can be referred to one of three subgroups known as kaolinite, illite and montmorillonite.

The term kaoline originates from the name of a Chinese hill where this product was extracted for centuries. In China kaolinite locality called "Kauling" meaning high ridge. The structure of kaolinite was established by Gruner in 1932 and revised by Brindley and Robinson in 1946 (cited by Millot, 1970). Kaolinite is formed by the breakdown of feldspar by the action of water and carbon dioxide (Craig, 2000). Murray (1999) described that Kaolines are most often formed by the alteration of Al silicate minerals in a warm, humid environment. Usually Kaolinite can be found in the colours of white to cream and pale-yellow, also often stained various hues, tans and browns. This mineral is the most dominant part of residual clay deposits and is made up from large stacks of alternating single tetrahedral sheets of silicate and octahedral sheets of aluminium. The structural formula of kaolinite is $(OH)_4 Al_2 Si_2$. The formula shows that the layer is electrically neutral; fourteen negative ions corresponding to the oxygen and hydroxyl groups balance the fourteen positive charges corresponding to the aluminium and silicon ions (Millot, 1970). Kaolinites have common impurities like: Fe, Mg, Na, K, Ti, Ca and H_2O. The combined silica-alumina sheets are held together fairly tightly by hydrogen bonding. So, Kaolinites are very stable with strong structures and absorb little water. They have low swelling and shrinkage response to water content variation. Specific gravity (G_s) of Kaolinites is 2.6 in average. One of the more important properties that many Kaolins exhibit is that they have good flow properties when present in large amounts in water. This is particularly important in one of the major uses of Kaolin-the coating of paper. The reasons that kaoline has good rheology are that it has a low surface area, exhibits a good crystalline morphology and its particle size is fine with a broad particle size distribution (Murray, 1999). Kaolinite is important to the production of ceramics and porcelain. It is also used as filler for paint, rubber and plastics since it is relatively inert and is long lasting. But the greatest demand for kaolinite is in the paper industry to produce a glossy paper such as is used in most magazines.

Illite named in 1927 for one of the co-type localities, the one in Illinois, USA. Illites consist of a series of single octahedral sheets of aluminium sandwiched between two tetrahedral sheets of silicon. In the octahedral sheets some of the aluminium is replaced by iron and magnesium and in the tetrahedral sheets there is a partial replacement of silicon by aluminium. The structural formula of illite is $(OH)_2 (Al, Ti, Mg, Fe)_2 (Si_{4-x} Al_x)_{10} - (Ca, Na, K, H_3O)_x$. Millot (1970) showed that Illites are the most common clay minerals in nature. Usually it can be found in the colours of grey-white to silvery-white, greenish-grey, sometimes stained other hues. Illites tend to absorb more water than Kaolinites and have higher swelling and shrinkage characteristics.

Montmorillonite discovered in 1847. This mineral has a similar structure to the illite group but, the bonds between layers are weakened and also, in the tetrahedral sheets, some of the silicon is replaced by iron, magnesium and aluminium. Montmorillonites give evidence of extreme high water absorption, swelling and shrinkage characteristics. The structural formula of montmorillonite can be written as $(Na,Ca)_{0.33}(Al,Mg)_2(Si_4O_{10})(OH)_2 \cdot nH_2O$. Bentonite is a member of this mineral group and is usually formed from weathered volcanic ash. Bentonite has large expansive properties, when it is mixed with water. Accordingly, it is much in demand as a general grout in the plugging of leaks in reservoirs and tunnels. It is also used as a drilling mud for soil borings. Bentonite gives water greater viscosity ("thickness" of flow), which is very important in keeping a drilling head cool during drilling and facilitating removal of rock and dirt from

within a drill hole. Montmorillonites have common impurities like Fe, K. Usually it can be found in the colours of white, grey or pink with tints of yellow or green. Specific gravity (Gs) of Montmorillonite is variable from 2.3 – 3.

Terzaghi and Peck (1993) reported that in problems interesting to civil engineers, clay particles are always in contact with water. The interactions among the clay particles, water, and the various materials dissolved in water are primarily responsible for the properties of the soil. The various clay minerals differ widely in their ability to adsorb cations; the approximate cation exchange capacity (expressed in terms of the total number of positive charges adsorbed per 100 gm) of different clay minerals with approximately equal particles size is shown in Table 1.

Table 1: Clay mineral charge adsorption (after Terzaghi and Peck, 1993)

Minerals	No. of positive charges adsorbed per 100 gm ($*10^{20}$)
Montmorillonite	360-500
Illite	120-240
Kaolinite	20-90

The adsorbed ions are not permanently attached to the clay mineral. If, for example, clay containing adsorbed ions of Na+ is washed by a solution of KCL, most of the Na+ ions are replaced by K+ ions. This process is known as cation exchange. According to Gergely (2010) there are two salinisation processes: primary and secondary. The primary salinisation involves salt accumulation through natural processes due to a high salt content of the parent material or in groundwater. The secondary salinisation is caused by human intervention such as inappropriate irrigation practices and insufficient drainage. Both of these salinisation processes can damage infrastructure (roads, foundation of structures, bricks, corrosion of pipes and cables). In addition, soil salinity has detrimental effects on plant growth and yield, promotes soil erosion and ultimately causes sedimentation problems.

Bentonite is widely used as a soil admixture for the construction of clay liners, seepage barriers and waste containment due to its high swelling and adsorption capability. In general, bentonite with high cation exchange capacity, surface area and liquid limit is preferable for waste containment systems. Previous studies have shown that when bentonite comes in contact with the salt solution, its properties such as the hydraulic conductivity and the Atterberg limits will be affected significantly (Mishra *et al.,* 2009). For instance, Nayak *et al.* (2010) found that the hydraulic conductivity of clayey soils increased with NaCl concentration whereas, liquid limit and plasticity index of the soils tested decrease as a result of interaction with sodium chloride solution. It can be noted that the extent of salt concentration and the type of soil are important parameters for the altered properties of the soil. This paper presents the results of several experimental tests to investigate effects of these factors in detail. The findings of this research are in good agreement with previous studies conducted by Nayak *et al*. (2010) and Mishra *et al*. (2009).

Saline water intrusion into coastal aquifers is a commonly occurring phenomenon, especially in densely populated areas due to excessive pumping of groundwater (Zhou *et al.,* 2009). Continuous contact of the aquifer material with the intruded sea water initiates progressive alteration in the geotechnical properties of the soil, especially the hydraulic conductivity (Mishra *et al*., 2006). In order to investigate and analyse the pattern of saline water intrusion into the fresh water aquifers in the coastal zones and hence evaluate the permissible discharge for withdrawal of groundwater so as to ensure that the fresh water zone is not affected adversely with saline water intrusion, appropriate value of the altered hydraulic conductivity of the aquifer material should be estimated (Bhattacharya *et al.,* 2004-2006).

The changes in hydraulic conductivity of soils varying in calcite content under several consecutive cycles of irrigation with saline waters of sodium adsorption ratio (SAR) and simulated rain water has been studied by Minhas *et al*. (1999). Significant reductions in the hydraulic conductivity with SAR were observed, the major reductions occurring when the columns were leached with simulated rainwater (SRW), with the effects being accentuated with increasing SAR. In the analytical study made by Ichikawa *et al*. (2001) on seepage and consolidation of bentonite saturated with saline water, the alteration of hydraulic conductivity with the interlamellar distance was observed to be effected significantly due to salt water. Mishra *et al*. (2005 & 2006) conducted a series of laboratory experiments by means of consolidometer permeameter to study the effect of salt concentrations on the hydraulic conductivity of the mixtures of Basalt soil and various bentonites. It was observed that the intrusion of salt increases the hydraulic conductivity of the soil mixture, although no definite pattern of increment could be concluded specifically for NaCl solution. An increment of the NaCl concentration from 0 to 0.1 mol/L initiated the hydraulic conductivity of the soil mixture to increase by about 2 to 4 times. Zhou *et al*. (2009) carried out a laboratory study to investigate the permeability changes during remediation of an

aquifer affected by seawater intrusion. The results indicted that gradual changes in the salinity lead to less reduction of permeability, which introduced the significance of maintaining gradual salinity gradients during displacement for better sustain aquifer permeability during remediation of seawater intrusion.

3   LABORATORY EXPERIMENTS

Clays passing a 425 μm sieve and prepared in accordance with AS 1289.1.1 have been employed. Two commercially available clay types namely Kaolinite (Q38) and Bentonite (Active Bond 2-3) were selected. Natural fine sand passing 425 μm sieve has been used for sample preparation with various sand content (0 - 30%). Effect of salt content (sodium chloride, NaCl) has been investigated in two ways; (i) conducting the tests using salty water with different salt concentration (0 – 200 g/L), and (ii) adding different portions of dry salt to the dry soil (0 – 20%) and adding distilled water to the final mixture. After adding distilled/salt water and mixing the soil, resulting in a thick and homogenous paste, the wet soil mixture has been cured for at least 12 hours at constant room temperature. Oven drying temperature of 105-110°C has been used for moisture content determination. The methods recommended in AS 1289.3.9.1—2002 considering drop-cone penetrometer to measure liquid limit of soils has been adopted in this study. A cone of weight 80 grams with an apex angle of $30^o \pm 1^o$ fixed to a vertical sliding shaft is positioned with its tip just flush with surface of clay filled a standard cup. The cone is released for penetration under its own weight. The soil is then remixed and the measurement repeated. If the penetration measured in the two trials is different by less than 0.5 mm, the water content is determined. The water content of clay corresponding to 20 mm in 5 ± 0.5 sec is assumed to be the liquid limit of the soil. It should be noted that the results should be plotted in log-linear scales; moisture contents as linear coordinates and corresponding cone penetrations as log abscissae. Then a straight line of best fit will be plotted for data points. On that line, the moisture content corresponding to a cone penetration of 20 mm is determined. This moisture content is the cone liquid limit of the soil (w_{cl}). Figures 1 and 2 present examples illustrating the data interpretation to estimate Liquid Limits of the kaolinite and the bentonite with distilled water and no fine sand content, respectively (Log 20=1.301).
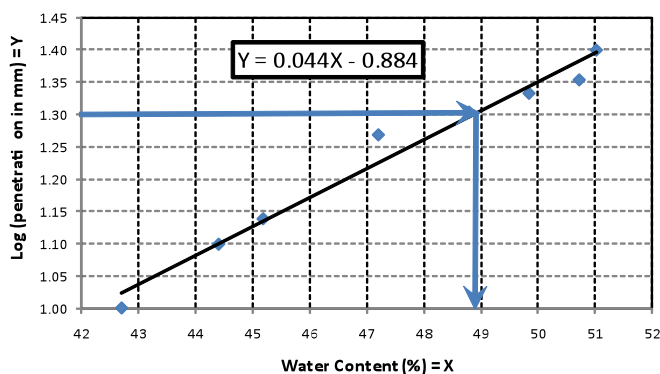

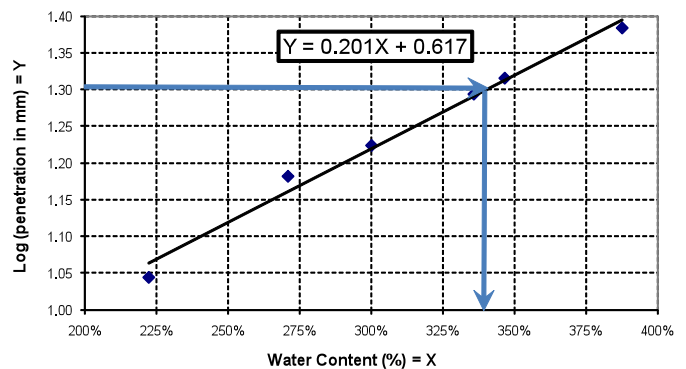Figure 1: Estimation of kaolinite liquid limit with distilled water and no sand content

Figure 2: Estimation of bentonite liquid limit with distilled water and no sand content

To investigate the effect of salinity on hydraulic conductivity of subsoil aquifer stratum, the soil sample was collected from a coastal area of the East Midnapore district state of West Bengal, India. As obtained from the bore log data, the subsoil existing in the region consists of laterite silty clay up to a depth of about 2 m below ground surface, silty fine sand between 2-15 m depth, stiff sandy silty clay between 15-30 m depth, and dense sand beyond 30 m depth. The groundwater table was situated at a depth of 3 m below the ground surface. The sample collected for laboratory tests was obtained from a depth of 5 m below the ground surface, i.e., the first aquifer strata. Prior to conducting laboratory tests, the sample was initially air dried for one month. The sieve analysis and hydrometer test results indicated that the soil contains 52% of fine sand, 41% of silt and 7% of clay. The electrical conductivity of the soil sample, which was measured following the method of Jayasekara *et al.* (2007), was observed as EC_e=2.3 μS/cm. The chloride concentration obtained from chemical analysis of the water sample collected from the site tapping the first aquifer layer was observed to be as low as 0.05g/L, which indicates that the groundwater as well as the aquifer has not been affected significantly by saline water intrusion. The pH value was found to be 7.2, which indicated slight alkaline nature of the groundwater in that region.

To study the influence of salinity on the hydraulic conductivity of the soil, selected soil masses were submerged at room temperature (25^0C) in salt water (i.e., solutions prepared by dissolving NaCl in distilled water) at different concentrations starting from zero (i.e., fresh water) to as high as 357 g/L (i.e., saturated solution at 25^0C) with different periods of submergence from 0-14 days. The submerged soil mass was then withdrawn

from the solution tested for hydraulic conductivity by constant head permeameter with the same NaCl solution under which it was submerged. The soil mass was filled in the permeameter mould by compacting to standard Proctor maximum dry density following ASTM recommendation (Nayak *et al.*, 2010 and Moayed et al., 2011). Prior to the commencement of the actual test, the salt water was initially allowed to pass through the soil freely (Zhou *et al.*, 2009) for about 1 hour. The hydraulic conductivity of the soil was evaluated by using the equation suggested by Uppot *et al.* (1989), after measuring separately the mass density and viscosity of each of the salt-water solutions by Wesphal Balance and Saybolt's Universal Viscometer, respectively. The variation of the viscosity and density of the solution with increasing salt content has been reported elsewhere (Bhattacharya *et al.*, 2004).

4 RESULTS AND DISCUSSION

Tables 2 and 3 summarise the test results on the effect of salt concentration in mixing water on the liquid limit of various kaolinite, bentonite and sand mixtures. In addition, results have been plotted in Figures 3 and 4.

Table 2: The effect of fine sand content and water.

		Fine Sand Content (%)				
		0	5	10	15	20
Salt Content in Mixing Water (g/L)	0	48.9	46.6	45.6	44.1	41.2
	50	48.6	45.9	45.5	43.2	41.0
	100	48.3	45.3	44.5	42.4	40.8
	150	47.2	44.8	43.1	41.1	39.5
	200	46.1	44.3	42.1	40.4	37.8

Table 3: The effect of fine sand content and water salinity on liquid limit of Bentonite clay.

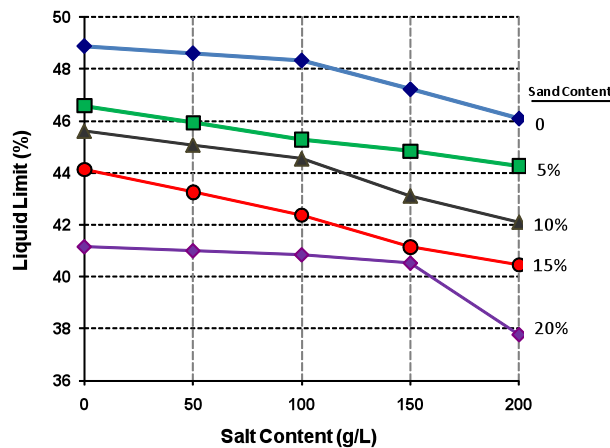|		Fine Sand Content (%)						
		0	5	10	15	20	25	30
Salt Content in Mixing Water (g/L)	0	340.3	317.0	294.4	266.5	254.4	246.9	230.4
	50	234.5	218.3	202.7	183.5	175.2	170.1	158.1
	100	181.4	169.0	156.9	142.0	135.6	131.6	122.8
	150	175.1	164.0	151.3	138.1	130.9	127.6	119.2
	200	170.0	159.0	146.7	134.1	127.1	123.6	115.6

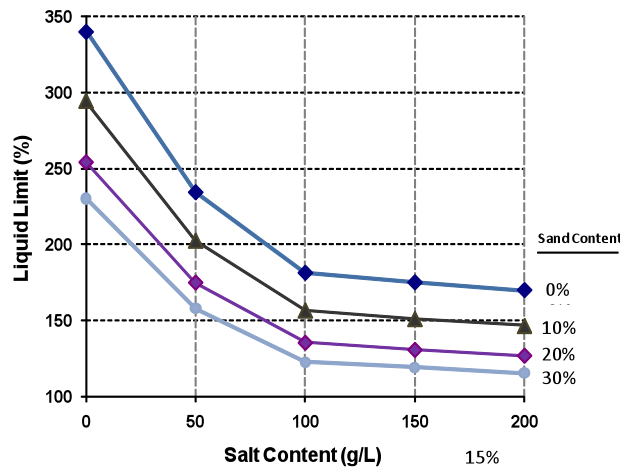Figure 3: Effects of water salinity and soil sand content on Liquid Limit of Kaolinite clay.

Figure 4: Effects of water salinity and soil sand content on Liquid Limit of Bentonite clay.

According to the results presented in Table 2 and Figure 3, liquid limit of Kaolinite clay decreases by both water salinity and fine sand content. For fresh (distilled water) the increase in the fine sand content from 0% to 20% induces a 16% decrease in the liquid limit. For pure kaolinite (no fine sand content), an increase of water salinity from 0 to 200 g/l sodium chloride, results in a 6% decrease in the liquid limit. The influence of fine sand content and water salinity has also been investigated for bentonite clay and the results have been reported in Table 3 and Figure 4. Similar to kaolinite results, the liquid limit of bentonite decreases with increase in water salinity and fine sand content. However, the influence of salinity is more significant for bentonite in comparison to kaolinite. When water salinity increases from 0 to 100g/L, liquid limit of pure bentonite (no fine sand content) decreases by 47%. Furthermore, increasing the fine sand content from 0 to 30% for bentonite and distilled water mixture, results in 32% decrease in the liquid limit. Vembu and Wilbourn (2007) performed experiments to analyse the liquid limit, moisture density and optimum moisture content (OMC) relationships for bentonite-sand and kaolinite-sand mixtures. From their laboratory experiments, it has been found that the liquid limit and plasticity index of soil increases with increase in clay content (or decrease in fine sand content) which is in good agreement with the results reported in the current study. This behaviour is due to the decline in the thickness of the subtle double layer as the fine sand content increases. Abood *et al.* (2007) reported similar results concluding that the liquid limit decreases with the increase in salt content. This downward inclination can be explained in terms of the interparticle forces that play a major role in establishing the liquid limit. With the rise in salt concentration, interparticle repulsion in clay diminishes and the particles become free to move at less interparticle distance affecting a decrease in the liquid limit (Higashi *et al.*, 2009).

The results reported in Figures 5 and 6 confirm effect of salt content (sodium chloride) as the percentage of solid mass on the liquid limit values of Kaolinite and Bentonite.
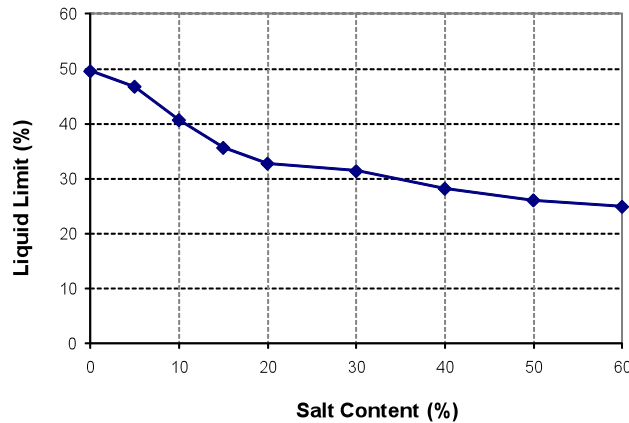
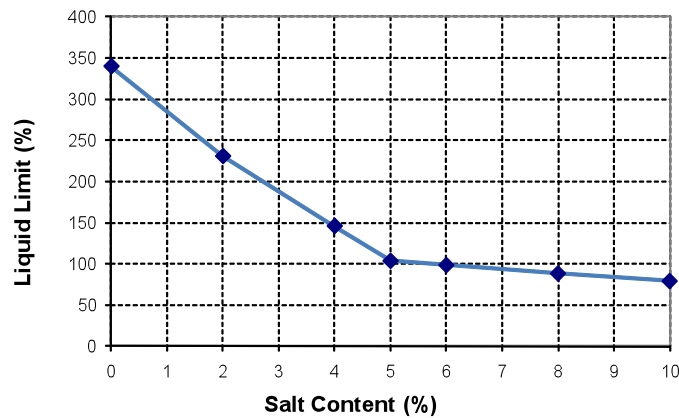Figure 5: Effects of soil salinity on Liquid Limit of Kaolinite clay.

Figure 6: Effects of soil salinity on Liquid Limit of Bentonite clay.

According to Figures 5 and 6, nearly 50% and 70% of decrease in the liquid limit occurs with 20% and 5% salt concentration increase for kaolinite and bentonite, respectively. The results show that the liquid limit of clays decreases significantly with an increase in NaCl concentration from 0 to 20%, and 0 to 5%, for kaolinite and bentonite, respectively. However, a further increase in the concentration does not result in any significant decrease in the liquid limit. These results are aligned with the results from a study carried out by Schmitz and Paassen (2003) revealing that increasing salt concentration would cause considerable changes in properties such as decay in liquid limit of clay. The exchangeable cation present from the addition of salt would cause interlayer spacing of kaolinite and bentonite to move freely relative to each other, resulting in the decrease in liquid limit (Mishra *et al.*, 2008). According to Tiwari *et al.* (2005) and Mitchell (1993), thickness of the double layer decreases with the increase in NaCl concentration in pore fluid, which causes ion diffusion into the fluid. Such a phenomenon decreases osmotic repulsion and consequently increases the effective normal stress.

The permeability test results are summarised in Table 4. The variation of hydraulic conductivity of the soil with the salt concentration and the period of submergence are plotted in Figures 7 and 8, respectively.

Table 4: Values of measured hydraulic conductivity of soil.

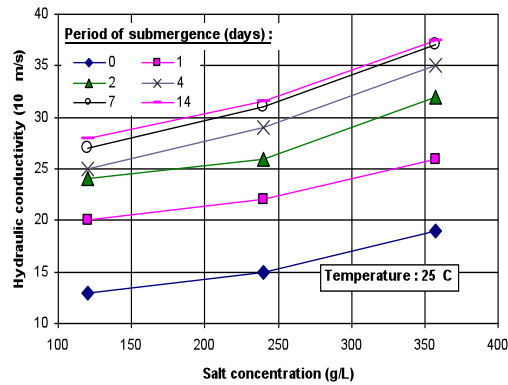| Concentration of salt water (g/L)	Period of submergence (days)	Hydraulic conductivity (10^{-6} m/s)
0	0	11
120	0	13
	1	20
	2	24
	4	25
	7	27
	14	28
240	0	15
	1	22
	2	26
	4	29
	7	31
	14	32
357*	0	19
	1	26
	2	32
	4	35
	7	37
	14	38
* Saturated NaCl solution at a temperature of 25°C;		

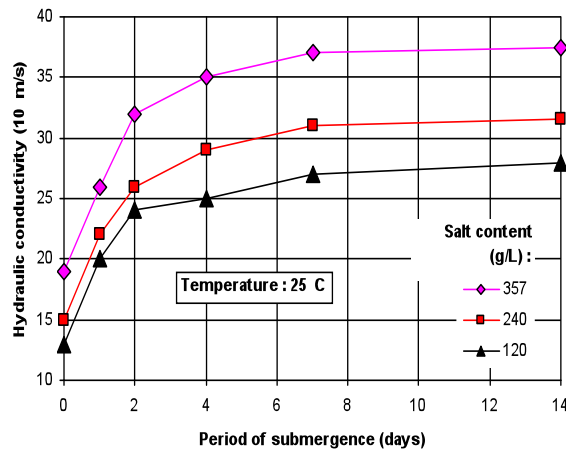Figure 7: Variation of hydraulic conductivity of soil with salt concentration.

Figure 8: Variation of hydraulic conductivity of soil with period of submergence.

As observed, hydraulic conductivity increases non-linearly with salt concentration, but no definite pattern could be concluded. With the period of submergence, on the other hand, the hydraulic conductivity of the soil increases following an asymptotic manner. The increase is significant up to a period of submergence of 4 days, after which a stabilising tendency has been noted. The hydraulic conductivity increases from 11 x 10^{-6} m/s for fresh water to as high as 38 x 10^{-6} m/s (about 3.45 times) with saturated saline water at a period of submergence of 14 days. Also as observed from Figure 7, increase in the salt concentration initiates a gradual increment in the gradients of the curves. The increase in salt concentration as well as the period of submergence can be attributed to a decrease in the diffuse double layer thickness, resulting in larger intergranular pores (Mishra *et al*., 2005-2009; Nayak *et al.,* 2010). Also, with increasing saline concentration, although the viscosity of the solution increases considerably, the subsequent increase in its mass-density is insignificant. These two factors have affected the increase in the hydraulic conductivity of the soil with both the salt content and the period of submergence (Uppot *et al*., 1989). The practical significance and engineering application of the above study are to get a rough idea about reasonably estimating the field hydraulic conductivity of coastal aquifers in conditions similar to the laboratory experiments and thereby carrying out analysis of the degree and extent of the saline water intrusion and predicting the allowable discharge of groundwater withdrawal.

5   CONCLUSIONS

The liquid limit of soil varies depending on many factors, including the characteristics of the particles (concentration, morphology, reactivity or size) and the liquid characteristics (e.g. salinity, pH, or chemical properties). The first part of this investigation has been performed to observe the effects of salinity and fine sand content on the liquid limit of fine grained soils. Liquid limits of kaolinite and bentonite clay decline as the salt content increases. As stated by AS 1289.3.9.1 – 2002, the only solution used to determine liquid limit is distilled water. Whereas, from the experiment, it can be observed that the accretion of salinity also has a significant influence upon the liquid limit of clays. Thus, salinity is one of the factors which has an impact on clay behaviour and needs to be considered in standardised testing methods. In addition, Atterberg limits are used to categorise fine-grained soil materials (passing 75μm sieve); however, according to AS 1289.3.9.1 – 2002, the soil shall be separated on a 425 μm sieve. According to the laboratory results, liquid limit values of kaolinite and bentonite clays decline with the addition of fine sand content. The addition of sand particles affects the liquid limit of clays even though the sand particles have already been sieved through a 425 μm sieve. It can be concluded that the use of 425 μm sieve in standardised test method on testing liquid limit of soil is somehow irrelevant as the size of fine soil particles are less than 75μm and not 425 μm.

The second part of this experimental study is associated with the variation of the soil hydraulic conductivity with saline concentration and its contamination time. An array of tests was conducted using fine sand, collected from a coastal region of India. Permeability tests were carried out employing a constant head permeameter with salty water at various concentrations and submergence periods. The soil hydraulic conductivity was observed to increase non-linearly with the salt concentration, but no definite pattern could be concluded. On the other hand, with increase in the period of submergence, the hydraulic conductivity of the soil increases asymptotically. The increase being significant up to 4 days, after which a stabilising tendency was noted. Due to excessive pumping of groundwater, saline water intrusion takes place in the coastal aquifers, inducing remarkable alteration in the geotechnical properties of the aquifer soil, especially the hydraulic conductivity. The appropriate choice of hydraulic conductivity of the coastal aquifer is of utmost importance so as to reasonably estimate the allowable limit of the rate of extraction of groundwater to ensure the fresh water zone is not significantly affected by salt water. The laboratory test results presented in this paper are useful in predicting the hydraulic conductivity of coastal aquifers in field conditions similar to the laboratory experiments.

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